*Wordcount: 9534 (including references)*

# A critical review of the greenhouse gas emissions associated with parabolic trough concentrating solar power plants

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## Abstract

Numerous research studies have focused on the Life Cycle Assessment (LCA) of solar energy systems, and more concretely, within the last decade, on the environmental performance of parabolic trough solar power plants. Due to ever-increasing global energy demands, the optimization of energy solutions to reduce adverse environmental impacts has been attracting research efforts. The study presented herein reports on the environmental perspective of parabolic through concentrated solar power (CSP) plants, focusing on greenhouse gas emissions. Existing studies on the environmental impacts of parabolic trough CSP plants show significant differences regarding the scope and frontiers of the LCA, database employed, raw materials, lifetime of the CSP plant, and temporal assumptions. The convergences and divergences appearing in the most relevant papers are recompiled, disaggregated by system and LCA phase, identifying the parameters with higher impacts and calculating the influence on environmental issues. The scientific literature review carried out demonstrated a knowledge gap on inventory data for parabolic trough CSP plants. This study provides a framework for the establishment of energy policies and standards, along with data for the environmental optimization of parabolic trough CSP plants.

## Keywords

Carbon footprint; Parabolic trough; Concentrated solar power

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## 1. Introduction

Because of the recent increase in global energy-related carbon emissions (the highest rate since 2013), the International Energy Agency (IEA) is investigating how advancements on energy efficiency can be accelerated by implementing stronger policy actions (International Energy Agency (IEA), 2019) . The research efforts carried out in the 1990s and 2000s on wind and solar power have shown relevant benefits, increasing the competitiveness of generation costs (International Renewable Energy Agency (IRENA), 2019).

The development of clean energy technologies must be accelerated to overcome global challenges associated with climate change and sustainable development. The use of renewable energy technologies for the generation of electricity and heat is a crucial action to reduce environmental loads (Qi et al., 2014). The life cycle greenhouse gas (GHG) emissions of conventional sources are much higher than renewables, except for nuclear-based power electricity generation (Amponsah et al., 2014). The Renewables 2018 Global Status Report (REN21, 2018) mentioned that although the power sector is striving towards a renewable-based energy future, transition has been advancing slowly, and renewable energy accounted for only 18.2% of final global energy consumption in 2016.

Concentrating Solar Power (CSP) has been in the research spotlight recently as it presents better environmental results than other technologies (Desideri et al., 2013). When compared with fossil fuel-based competitors, CSP presents a much lower impact (Kuenlin et al., 2013). However, CSP performance could still benefit from economic optimization (Islam et al., 2018). In 2017, although the market for CSP had a global capacity of approximately 4.9 GW, there was only a slight increase in installed power regarding 2016 (REN21, 2018). The current CSP projects under construction are confined to emerging markets, with no new commissions in the traditional markets of Spain and the USA (REN21, 2018). As Achkari and El Fadar (2020) mentioned, significant improvements in CSP have been in the spotlight of research, along with the gathering of compelling evidence proving the importance of this technology.

The four most common CSP technologies are central tower, linear Fresnel, dish stirling, and parabolic troughs – the latter is considered the most mature commercially available technology (Giostri et al., 2012). Parabolic trough collectors (PTCs) are one of the most employed CSP (Reddy and Ananthsornaraj, 2020) technologies , especially in arid and semi-arid sites (Aqachmar et al., 2019). Recent investigations focus on the improvement of PTC performance (Abed and Afgan, 2020), and the studies can be classified into two types: those dedicated to improve thermal performance (Wang et al., 2019) and those focused on optical performance (Xu et al., 2019). Parabolic trough CSP plants present a longer, demonstrated commercial operational experience and less technical and financial risks (Achkari and El Fadar, 2020).

Life Cycle Assessment (LCA) quantifies the potential environmental impacts throughout the lifecycle (or during specific phases) and can provide the means to compare the sustainability of energy technologies (Bravo et al., 2014). Several LCA studies have focused on CSP, but the comparison of results is not straightforward. Considerable differences hinder the comparison of studies, such as LCA methodology, system location, database employed, level of detail and aggregation, and temporal assumptions, to name a few. Although a complete LCA encompasses several impact categories, the communication of GHG emissions[1] has become popular and is now widely disseminated in the media (Carvalho and Delgado, 2017), with a much broader appeal than LCA.

The Life Cycle Inventory (LCI) is a critical phase, especially within CSP technologies. The solar field and the storage system are responsible for the majority of environmental impacts (Ehtiwesh et al., 2016), due to the massive amounts of steel and synthetic oil, and molten salts, respectively. LCI results are also site-specific, as higher solar irradiation leads to higher outputs and, consequently, to lower environmental impacts per energy unit produced. The comparison of CSP LCI should take into account the electrical output and storage capacity of each system, as a higher storage capacity also increases the power of the solar field. Focusing on GHG emissions, the most recent reviews quantified emissions per energy output for different parabolic trough CSP plants. Burkhardt et al. (2012) aimed at minimizing confusion over CSP's GHG emissions profile and relative benefits compared to fossil-fueled generation technologies, and obtained median estimates of 26 g $CO_2$-eq/kWh for parabolic trough CSP plants, while the interquartile range of published estimates was 83 g $CO_2$-eq/kWh. Kommalapati et al. (2017) compiled GHG emission statistics and obtained 79.8 ± 67.82 g $CO_2$-eq/kWh for parabolic trough CSP plants. Lamnatou and Chemisana (2017) verified that most emissions were under 40 g $CO_2$-eq/kWh for parabolic trough CSP plants, but emphasize that the environmental profile is influenced by cooling and water use, materials, soiling, land use, lifetime of components, operation and maintenance needs, and location.

The scientific literature review carried out demonstrated a knowledge gap regarding the LCI of parabolic trough CSP plants. This study has a significant contribution and presents a critical review of LCA studies of parabolic trough CSP technologies, focusing on GHG emissions. The results presented can aid in the decision-making process towards the adoption of more sustainable energy schemes for electricity production. The main objective of the research presented herein is to analyze the GHG results of existing LCA studies of CSP technologies and categorize the influence of different parameters, providing clear values for CSP plant optimization and a framework to guide research efforts, which are valuable in informing policy and supporting practice.

## 2. Methodology

A systematic search for scientific studies published between January 1st, 2008 and May 1st, 2019 was carried out in the Google Scholar, Science Direct, Web of Knowledge, and Scopus databases. The following descriptors were employed, in the English language: life cycle assessment, environmental assessment, Concentrating Solar Power, and parabolic trough. Synonyms and acronyms were also utilized in varied combinations. Different combinations of descriptors were utilized to guarantee an efficient search strategy.

Inclusion Criteria: LCAs of parabolic trough CSP plants that included detailed LCI for the manufacturing phase were included in the assessment.

Exclusion criteria: Studies that did not follow ISO 14040 (2006) were excluded, along with results derived from books, proceedings, and conference abstracts. Studies that considered hybridization with fossil fuels to support electricity generation were also excluded.

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[1] Herein the terms GHG emissions and carbon footprint refer to the grouping of atmospheric emissions and conversion into a common metric, $CO_2$-eq (various greenhouse gases can be therefore compared on the basis of their Global Warming Potential, GWP).

Primary screening comprehended the reading of titles and abstracts of all studies identified in the searches (manual and in databases). Only studies focusing on the LCA of parabolic trough CSP plants were selected. Duplicated studies were removed. Secondary screening encompassed the full reading of studies, selecting those that fulfilled inclusion criteria and presented high methodological quality. Relevant data was collected, such as detailed Life Cycle Inventory (LCI) for the studied CSP plant (parabolic trough). A manual search was also carried out in the references listed in the studies that passed the secondary screening, for the inclusion of additional studies not identified in the electronic search.

After identification of the studies that presented detailed LCI data, these were critically compared. Software SimaPro v.9.0.0.35 (PRe Consultants, 2018) was employed herein to assess some stages of the inventory.

## 2.1 Life Cycle Inventory (LCI)

The LCI involves creating an inventory of input and output flows for a product system. For the CSP plants considered herein, the LCI included the material composition of the CSP plant itself (i.e., raw materials, manufacturing, transportation and distribution, use, maintenance, and final disposal). Figure 1 shows the system boundary of a solar CSP plant, and the different phases are explained next.

- Raw materials. This phase includes the extraction and processing of raw materials and transportation to the site.

- Manufacture of components and systems. This phase consists of the activities necessary to build the components, with five main subsystems:

  - The Solar Field (SF) is constituted by a set of solar collector assemblies (SCAs), which are independent tracking parabolic trough solar collectors (parabolic reflectors, receiver tube, metal support structure, and tracking system that includes the drive, sensors, and controls). Mirrors (parabolic reflectors) are used for the collectors and heliostats, mainly made of low iron glass (Kennedy, 2008). The main primary material employed is silica sand. The support structures are made of galvanized steel, and the absorber tubes are made of stainless steel (Pihl et al., 2012). A significant amount of concrete is used for the foundations of the solar field. Concrete constitutes the majority of the solar field inventory (mainly for trough anchorages) (Viebahn et al., 2008).
  - The Heat Transfer system (HTF) includes synthetic oil, pipes, and heat exchangers. Concrete, carbon steel, and the HTF itself are the most significant materials within this subsystem.
  - The Thermal Energy Storage system (TES) is composed of two tanks, pipes, foundations, insulation, nitrate salts, and heat exchangers. The tanks are made of carbon steel, and the tank walls are insulated with sand-lime bricks (calcium silicate) (Burkhardt et al., 2011).
  - The Power Block system (PB) includes the steam turbines and the pipes, pumps, heat exchangers, valves, and other small components. Steam turbines are mainly made of stainless steel. Heat exchangers and ducts are made of low-chromium steel and carbon steel (Pihl et al., 2012). Concrete and carbon steel are the most employed materials within this subsystem (Burkhardt et al., 2011).
  - The Building and Facilities (BF) encompass office buildings, storage facilities, roads, and parking. Concrete, rock, and gravel are the most used materials (Burkhardt et al., 2011).

- Operation and maintenance. Includes the activities, energy, and materials required for the operation of the plant.

- Dismantling and disposal. Includes the disassembly of the CSP plant and disposal scenario for its different constituting materials.

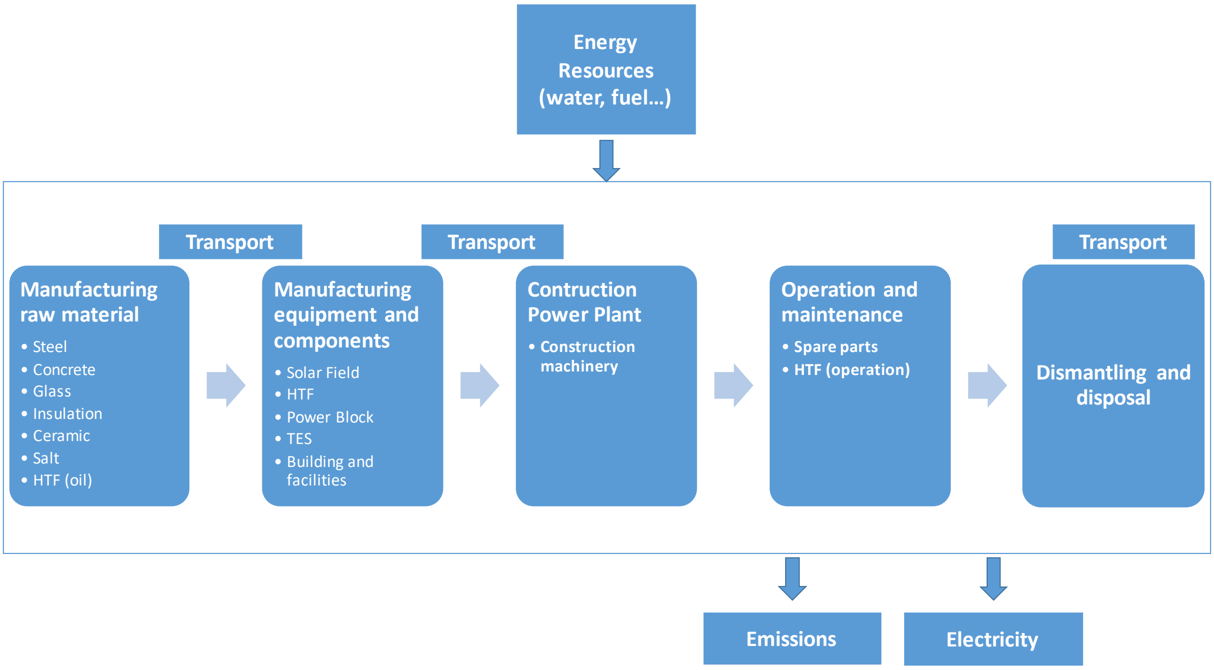

Figure 1. Lifecycle phases for the CSP power plant.

## 3. Results and discussion

### 3.1 Systematic scientific literature review

The literature search identified 96 studies from the aforementioned digital repositories. Exclusion of duplicated studies followed.

Primary screening eliminated 63 references from the initial 96 identified and therefore, only 33 studies were eligible for complete reading (Table 1A in supplementary material). Studies that did not fulfill the inclusion criteria were excluded. The secondary screen assessed the quality of the studies, and eliminated 26 references, leaving a total of seven studies.

Viebahn et al. (2008) presented detailed LCI data and associated key emissions for four types of solar thermal power plants (parabolic and Fresnel trough, solar tower, dish-stirling, and solar updraft tower plant). Two CSP parabolic trough plants were presented: Andasol I (46 $MW_e$), which was the first parabolic trough power plant in Europe and the first in the world with storage, and Inditep (5 $MW_e$). Both plants are located in Spain and are wet-cooled plants, with thermal energy storage (TES) based on molten salts for Andasol I, while Inditep has a direct steam generation system (DSG). LCI data for both plants presented a linear relationship with nominal net power for the phases: “Building and urbanization”, “Transport” for the construction phase, and “dismantling”. LCI data for the cooling tower also presented a linear relationship with nominal net power. There was no mathematical relationship between the LCI data of the solar field and the annual flows associated with operation and maintenance.

Burkhardt et al. (2011) reported a very detailed LCI of a parabolic trough concentrating solar power plant. The 103 $MW_e$ CSP facility is located in Daggett, USA, and presents a molten salt-based TES system. Results were presented for a wet-cooled and a dry-cooled system.

Adeoye et al. (2013) presented an LCA for a 100$MW_e$ (Shams1) CSP parabolic though plant, wet-cooled, located in the United Arab Emirates, with no TES. The study analyzed the environmental impact of two potential TES systems, molten salts *vs.* concrete, and the functional unit was 800MWh of electricity produced per cycle (one day). LCI covered the additional solar field and the concrete and molten salt storage systems.

Klein and Rubin (2013) studied a 110 $MW_e$ CSP Plant also located in Dagget, USA, with different backup energy options and with wet- and dry- cooling systems. LCI was based on Lüpfert et al. (2001) and Goswami DY and Kreith (2007).

Kuenlin et al. (2013) presented a LCA study for four different CSP plants: parabolic trough (Andasol I, based on manufacturer data), central tower, Fresnel, and parabolic dish. The parabolic dish plant (Maricopa) presented the best environmental performance while the parabolic trough plant presented the worst performance due to the utilization of synthetic oil and molten salts.

Corona et al. (2014) presented the LCI of a 50$MW_e$ CSP parabolic though plant, wet-cooled, located in Ciudad Real, Spain. The material composition was obtained directly from a technology expert, and inventory data was based on scientific literature for the raw materials, feed pumps in HTF circuits and TES, foundations for auxiliary boilers and TES, and for the power block's refrigeration system.

Ehtiwesh et al. (2016) presented LCI data for a 50 MW parabolic-trough based on Andasol I (Viebahn et al., 2008), and only the materials with significant contributions to the overall impact were mentioned.

More recently, Mahlangu and Thopil (2018) used the primary LCI Data from Burkhardt et al. (2011) and scaled it to represent a 100$MW_e$ solar plant located in Northern Cape, South Africa (0.97 factor).

Of the studies identified herein, Viebahn et al. (2008) and Burkhardt et al. (2011) presented the most complete and exhaustive LCIs, which have been the basis of more contemporary studies.

Six studies focused on wet-cooled CSP plants (Burkhardt et al., 2011; Corona et al., 2014; Ehtiwesh et al., 2016; Klein and Rubin, 2013; Kuenlin et al., 2013; Mahlangu and Thopil, 2018; Viebahn et al., 2008). Only Burkhardt et al. (2011) studied a dry-cooled CSP plant. The preference for wet-cooled plants was expected, as water is the preferred medium for power-cycle cooling, but availability can be limited by policy or cost in some locations. All CSP plants included Thermal Energy Storage (TES) with molten salts and employed solar energy exclusively.

Regarding the functional unit of the LCA studies, adequate selection of the functional unit is crucial to enable comparisons. Comparability of LCA results is particularly critical when different systems are being assessed, ensuring that comparisons are made on a common basis. The functional unit employed was the delivery of 1 $MWh_e$ by the CSP plant. Different levels of environmental impacts can be obtained depending on the location of the power plant: higher Direct Normal Irradiance (DNI) implies in higher electricity production, which leads to lower environmental impacts per MWh produced. The DNI is the direct irradiance received on a plane normal to the sun, which is very important to concentrated solar technologies as it represents the solar resource that can be used. The characterization of the solar resource currently corresponds to one of the leading research topics in the domains of solar radiation modeling and measurements (Blanc et al., 2014). It is very interesting to compare similar technologies with different DNI values, but the results are site-specific and, therefore, cannot be extrapolated to other locations. The first challenge for a researcher or professional working on the selection of sustainable solar solutions is that there are no environmental data available based on a functional unit independent of energy production and site.

A comparison of the LCIs for CSP plants also depends on storage capacity. Thermal storage capacity is expressed in terms of hours of power block capacity (equivalent full load hours), the number of hours during which TES can supply energy. As higher storage capacity increases the power of the required solar field, different storage capacities imply in different power plants. Hence, both load and storage must be taken into account.

Compilation of LCIs involves thorough, exhaustive data collection and calculation procedures to quantify the relevant inputs and outputs of a system. This process is iterative for CSP plants and is not straightforward. Real data is scarce due to a general lack of information, resistance to make data available, and because the environment and sustainable development are seen as issues and risk factors. However, as mentioned by Carvalho et al. (2016), these "issues" can also be seen as opportunities for growth and improvement of efficiency.

The different analysis tools used, calculation methods, databases, and year of publication affect the emissions and the environmental parameters obtained. Table 1 summarizes the relevant parameters utilized in the studies identified herein.

Table 1. Summary of parameters utilized by LCA CSP studies.

| Reference | (Viebahn et al., 2008) | (Burkhardt et al., 2011) | (Burkhardt et al., 2011) | (Klein and Rubin, 2013) | (Kuenlin et al., 2013) | (Corona et al., 2014) | (Ehtiwesh et al., 2016) | (Mahlangu and Thopil, 2018) |
|---|---:|---:|---:|---:|---:|---:|---:|---:|
| Database | NA | Ecoinvent v2.0 | Ecoinvent v2.0 | Ecoinvent | Ecoinvent v2.2 | Ecoinvent v2.2 | Ecoinvent v3 | Ecoinvent NA |
| LCA software | NA | SimaPro 7.1 | SimaPro 7.1 | SimaPro 7.1 | NA | SimaPro 7.3 | SimaPro 8 | GaBi LCA NA |
| Power ($MW_e$) | 46 | 103 | 103 | 110 | 50 | 50 | 50 | 100 |
| Location | Granada (Spain) | Daggett (USA) | Daggett (USA) | Daggett (USA) | Sevilla (Spain) | Ciudad Real (Spain) | Libya | Northern Cape (South Africa) |
| DNI ($kWh/m^2/yr$) | 2,136 | 2,700 | 2,700 | NA | 2,000 | 2,030 | NA | 2,900 |
| LC (years) | SF&PB 30 / TES 25/ B 60 | 30 | 30 | 30 | 25 | 25 | 25 | 20 |
| Net Power (MWh/y) | 158,000 | 426,700 | 438,800 | 443,000 | NA | 165,687 | NA | 320,000 |
| SF Aperture Area ($m^2$) | 510,120 | 987,500 | 1,063,000 | 810,000 | 500,292 | 510,120 | 510,120 | NA |
| Cooling | WC | WC | DW | WC | WC | WC | Wet-cooled | Wet-cooled |
| Molten Salts (tons) | 28,704 | 62,000 | 66,800 | 57,000 | 3950 | 28,000 | 25,600 | 60,800 |
| HTF (tons) | 1,995 | 4,270 | 4,600 | 2,300 | 1,990 | 1,000 | 1,995 | 4,150 |

*SF: Solar Field; PB: Power Block, TES: Thermal Energy Storage; B: Buildings*

*WC: wet-cooled; DC: dry-cooled*

### 3.2 Comparison of environmental impact assessment results

The calculation of GHG emissions is based on LCA but focuses on a single issue, which is global warming. Although the calculation of environmental impacts encompasses much more than GHG emissions, these present much broader appeal than a complete LCA: the calculated value can easily be "grasped" and placed in context (Weidema et al., 2008). Also, GHG emissions are significantly associated with energy use and have received more visibility because of the growing public interest in climate change (Carvalho et al., 2019).

GHG emissions (expressed in terms of $CO_2$-eq) were the most employed indicator to communicate the environmental impacts associated with CSP plants. The terms GHG emissions and carbon footprint are used interchangeably herein. Only two studies did not employ GHG emissions: Kuenlin et. al (2013) used the Impact2002+ method and Ehtiwesh et al. (2016) used the Eco-indicator 99 and Cumulative Exergy Demand methods. Five studies reported their emissions in terms of GHG emissions, shown in Table 2, in kg $CO_{2eq}$/MWh, for the CSP parabolic though wet-cooled plants.

Table 2. GHG emissions reported by scientific literature for CSP plants (wet-cooled), per MWh produced.

| | (Viebahn et al., 2008) | (Burkhardt et al., 2011) | (Klein and Rubin, 2013) | (Corona et al., 2014) | (Mahlangu and Thopil, 2018) |
|---|---|---|---|---|---|
| Power ($MW_e$) | 46 | 103 | 110 | 50 | 100 |
| LC (years) | SF30/-/PB30/TES25/B60 | 30 | 30 | 25 | 20 |
| kg $CO_2$ eq/MWh | 33 | 26 | 60 | 26.6 | 32.2 |
| kg $CO_2$ eq/MWh LC=30 | -- | 26 | 60 | 22.2 | 21.5 |

*SF: Solar Field; PB: Power Block, TES: Thermal Energy Storage; B: Buildings*

The difference between the results presented by Viebahn et al. (2008) and Burkhard et al. (2011) is due to the sizes of the plants considered. Viebahn et al. (2008) affirm that scaling the size up increases performance and reduces operation and maintenance costs. This consideration, however, is not applicable to Corona et al. (2014), who obtained lower values for a smaller CSP plant.

Klein and Rubin (2013) obtained the highest GHG emissions, and the authors explain that electricity-related emissions depend on the electricity mix used, and the values are based on the average California mix (mostly natural-gas-fired power plants). Burkhart et al. (2011) considered the average USA electricity mix, with higher GHG emissions, and obtained lower GHG emissions because of the annual auxiliary electricity used (4 GWh/yr) in comparison with Klein and Rubin (2013 (10 GWh/yr).

It must be highlighted that design features of the plants can affect the final environmental loads. Inherent to the design features, differences in performance also influence the specific environmental loads (kg $CO_2$-eq/kWh).

### 3.3 Comparison of lifetimes

The lifetime of the CSP plants and associated systems varied considerably across the studies, which strongly affected the resulting GHG emissions.

Viebahn et al. (2008) reported that increasing the lifetimes of the solar field, power block, and storage system by five years resulted in 15% fewer emissions. The authors proposed lifetimes of 30, 25, and 60 years for the power block and solar field, TES, and the buildings, respectively. The study developed a future scenario, proposing an increase in the lifetime of all systems (except for buildings). In a first step, for 2025, the lifetimes of the solar field and the power block will increase from 30 to 35 years while the lifetime of the storage system will increase from 25 to 30 years. Traditional fossil fuel power plants have usual lifetimes of 40 years, which means that specific material consumption and the resulting emissions are lower. In a second step, for 2050, the lifetimes of the solar field and power block will be increased to 40 years while the lifetime of the storage system increases to 35 years.

Burkhardt et al. (2011) and Klein and Rubin (2013) consider a lifetime of 30 years for all the systems, while Corona et al. (2014) considered 25 years and Mahlangu and Thopil (2018) considered 20 years.

The GHG emissions disaggregated by phase were published only by four studies, of which only Burkhardt et al. (2011) and Klein and Rubin (2013) presented the values disaggregated per subsystem for the manufacturing phase. Table 3 shows the GHG emissions, disaggregated, and normalized for a lifetime of 30 years, for comparison purposes.

Table 3. Disaggregated GHG emissions by phase, normalized to a lifetime of 30 years.

| Reference | | (Burkhardt et al., 2011) | (Corona et al., 2014) | (Mahlangu and Thopil, 2018) | (Klein and Rubin, 2013) |
|---|---|---|---|---|---|
| Manufacturing | SF | 4.6 | 17.58 | 9.40 | 9 |
| | HTF | 2.5 | | | 1.5 |
| | PB | 1.9 | | | 2 |
| | TES (MS) | 2.7 | | | 3 |
| Construction | Plant& Building& Facilities | 1.7 | 0.03 | 2.07 | 5 |
| O&M | | 10 | 3.86 | 4.87 | NA |
| D&D | | 2.22 | 0.75 | 5.13 | NA |
| Total | kg $CO_{2eq}$/MWh | 25.7 | 22.2 | 21.5 | 60 |

### 3.4 Comparison of HTF

The HTF employed in the identified publications is a synthetic oil: Therminol VP-1, which is a mixture of 73.5% of diphenyl oxide (DPO, $C_{12}H_{10}O$) and 26.5% of biphenyl ($C_{12}H_{10}$). DPO can be produced by dehydrating phenol over a catalyst (Burkhardt et al., 2011). Starting from the chemical reaction, the masses of the reactants can be calculated, and their environmental impacts can be quantified by SimaPro (PRe Consultants, 2018). Biphenyl is usually produced by the dehydrocondensation of benzene (and can be modeled within SimaPro). The GHG emissions, however, could be overestimated as the databases within SimaPro do not have a single datasheet for Therminol-VP1 or any of its components (phenol is used as a proxy for the diphenyl).

Table 4 shows the amount of HTF included by authors (Manufacturing and O&M phases) for 1 MWh of delivered electricity, considering the same lifetime (30 years) for comparison purposes.

Table 4. HTF amount included in the selected studies.

| Reference | (Viebahn et al., 2008) | (Burkhardt et al., 2011) | (Kuenlin et al., 2013) | (Klein and Rubin, 2013) | (Corona et al., 2014) | (Ehtiwesh et al., 2016) | (Mahlangu and Thopil, 2018) |
|---|---|---|---|---|---|---|---|
| Power ($MW_e$) | 46 | 103 | 50 | 110 | 50 | 50 | 100 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Net Power (MWh/y) | 158,000 | 426,700 | NA | 443,000 | 165,687 | NA | 320,000 |
| HTF (tonnes) | 1,995 | 4,270 | 1,990 | 2,300 | 1,000 | 1,995 | 4,150 |
| HTF (kg/MWh) LT=30 years | 0.42 | 0.33 | -- | 0.17 | 0.20 | -- | 0.43 |
| O&M HTF (tonnes) | 2,242.5 | 439 | NA | 350 | 10 | NA | NA |
| O&M HTF (kg/MWh) LT=30 years | 0.47 | 0.03 | -- | 0.03 | 0.002 | -- | -- |
| TOTAL HTF (kg/MWh) LT=30 years | 0.89 | 0.37 | -- | 0.20 | 0.20 | -- | 0.43 |

The amount of HTF included per $MW_e$ is, in three cases, approximately 40 t/$MW_e$. Nevertheless, Corona et al. (2014) and Klein and Rubin (2013) presented much lower values, 20 t/$MW_e$. Table 4 does not include values from Ehtiwesh et al. (2016) and Kuenlin et al. (2013) because these studies did not present annual electricity values for the studied CSP plant.

Additional HTF could be required (maintenance) because of vaporization or degradation due to operation temperatures. Some authors do not clarify whether extra HTF is needed for the maintenance and operation phases. Viebahn et al. (2008) included 89.7 t/year of HTF for a 25-year lifetime (2240.5 t), which is a very significant amount when compared with the other authors.

The amount of HTF affects the environmental emissions, however the method used to calculate the emissions associated with the manufacturing processes of the HTF is also very relevant. Table 5 shows the emissions obtained from Simapro 9.0.0.35 (PRe Consultants, 2018) for 1 kg of HTF, and then calculates the emissions considering the amounts reported by each study. The far right column presents the emissions reported by the studies.

Table 5. HTF emissions according to different manufacturing processes.

| Reference | HTF in LCA | kg $CO_{2eq}$ per 1 kg of HTF Ecoinvent 3.5 SimaPro 9.0.0.35 | kg $CO_{2eq}$/ MWh | kg $CO_{2eq}$/ MWh as reported by the studies |
|---|---|---|---|---|
| (Viebahn et al., 2008) | Diphenyl Ether 73.5% and phenol 26.5% (w/w) | 10.17 | 9.05 | 0.89 |
| (Burkhardt et al., 2011) | Emissions associated with the manufacturing process were provided by the manufacturer<br>DPO production calculated via Direct phenol method (73.5% w/w)<br>Biphenyl produced via the dehydrocondensation of benzene (26.5% w/w)<br>Ecoinvent v.2.0 database | 2.12 | 0.78 | 0.37 |
| (Kuenlin et al., 2013) | Diphenylether-compounds, RER<br>Ecoinvent v.2.2 database | 9.26 | -- | -- |

| | | | | |
|---|---|---|---|---|
| (Klein and Rubin, 2013) | Phenol as a proxy for diphenil component (Phenol, at Resource extraction, refining and production plant/RER S) and the average results for coke, crude oil and natural gas were used for biphenyl | 3* | 0.606 | 0.20 |
| (Corona et al., 2014) | 73.5% w/w Diphenylether-compounds, ay regional storehouse/RER S<br>26.5% w/w Phenol, at Plant/RER U<br>Ecoinvent v.2.2 database | 10.17 | 2.05 | 0.20 |
| (Ehtiwesh et al., 2016) | Diphenylether-compound, RER, Production; Alloc Def. U<br>Ecoinvent v.3 database | 9.26 | | -- |
| (Mahlangu and Thopil, 2018) | NA | -- | -- | 0.43 |

(*value according to the author)

Table 5 includes the kg $CO_2$-eq emitted by the HTF (per MWh for a lifetime of 30 years) when using the declared quantities for each author. The discrepancies obtained are considerable.

Ehtiwesh et al. (2016) and Kuenlin et al. (2013) used the Ecoinvent processes for Diphenylether-compounds, and the emissions obtained are similar to those obtained from the mixture Diphenyl Ether 73.5% and phenol 26.5% (w/w) used by Viebahn et al. (2008) and Corona et al. (2014). However, the emissions obtained by Burkhardt et al. (2011) are much lower, which considers that DPO production employed the direct phenol method (73.5% w/w) and that biphenyl was produced via the dehydrocondensation of benzene (26.5% w/w). These emissions are of the same order of magnitude of Klein and Rubin (2013), who did not present details on the manufacturing method of HTF but provided the emissions in kg $CO_2$-eq per 1 kg of HTF.

### 3.5 Comparison of TES and molten salts

TES technology solves the difference in time between the supply of solar energy and demand for electricity, providing advantages to CSP plants in comparison with other renewable energy technologies (Liu et al., 2016). A CSP Parabolic trough usually includes TES to improve competitiveness and provide a stable energy supply (Zhang et al., 2013). TES systems have an essential role in CSP plants, even though it is one of the less-developed systems (Oró et al., 2012). Sensible heat storage can use solid or liquid media, with the application of solid media being an adequate selection regarding investment and maintenance costs. Concrete is selected mainly due to its low cost, easy processing, and mechanical properties. Laing et al. (2006) developed high-temperature concrete and ceramic systems to be used as TES for parabolic trough power plants, using synthetic oil as HTF. The most deployed technology in CSP plants is sensible heat storage in liquid media, where the TES system presents two tanks (cold and hot). The molten salts are the most mature storage technology, and most plants incorporate this technology (Liu et al., 2016). The excess heat collected in the solar field warms the molten salts, which flow from the cold tank to the hot tank through a heat exchanger. The heat stored in the hot tank can be reverted to the salts and conducted to the steam generator.

The volume of the TES affects the environmental performance of the manufacturing phase, although its thermal capacity strongly influences the electricity produced by the CSP plant. Therefore, the design of the TES is a relevant task within the system configuration. Klein and Rubin (2013) found that CSP plants with TES generally emitted twice the GHG emissions as the minimal backup plants. The TES system presents a modular design (Burkhardt et al., 2011), and therefore double capacity will require double the materials.

Two studies utilized the Eco-Indicator 99 (EI99) method in their LCAs, in a cradle to grave approach. On the one hand, Oró et al. (2012) compared three different TES systems used in CSP plants: solid media (concrete), molten salts, and a PCM system. The two-tank molten salts TES system presented the highest environmental impact, and the main cause was the manufacturing phase. The highest impact was associated with the storage material, which is a mix of salts ($KNO_3$ and $NaNO_3$). The impact of each system per kWh of stored energy was evaluated. On the other hand, Adeoye et al. (2013) crried out the LCAs of two TES technologies (concrete and molten salts) for the Shams-1 CSP plant located in the United Arab Emirates. Both systems were designed for 8 hours of full-load electricity generation (100MW). The functional unit was 800MWh electricity produced per cycle (8 hours, one day). The amounts of molten salt and concrete needed were calculated based on previous studies, assuming a linear correlation between the storage capacity and the amount of construction materials. In this case, the authors concluded that most of the impact for both TES systems came from the manufacturing and construction phases and that the concrete TES presented higher environmental impact. The divergences across the results evidence the importance of defining international functional units, similar limitations, and comparable scopes. LCA studies on CSP are still limited, with few studies devoted to the TES unit (Lalau et al., 2016).

Molten nitrate salt, 60 wt% sodium nitrate ($NaNO_3$) and 40 wt% potassium nitrate ($KNO_3$), is an extended storage medium, being a stable mixture with low vapor pressure. Nitrate salts can be mined or produced synthetically, where 60% of the market share is obtained from mining (Burkhardt et al., 2011). Some of the authors consider that the salts are mined (Burkhardt et al., 2011; Klein and Rubin, 2013) while others consider the synthetic process (Corona et al., 2014; Ehtiwesh et al., 2016; Kuenlin et al., 2013; Viebahn et al., 2011). These considerations have a significant impact on the LCA and it is essential to specify the source of the salts in the LCA. Synthetic salts have environmental impacts one order of magnitude higher than mined salts (Burkhardt et al., 2011). García-Olivares et al. (2012) suggested that the natural reserves of nitrate salts are relatively small and that synthetic production of salts is required. The majority of the mines are located in Chile, and Burkhardt et al. (2011) reported the GHG emissions of mined nitrate salt from the major manufacturer in Chile.

SimaPro (PRe Consultants, 2018) databases do not include any datasheets for mined salts. Klein and Rubin (2013) explained the mining process and selected a similar method from the databases within SimaPro to represent surface mining with explosives (‘*verniculine, at mine/kg/ZA with US electricity*’) and crushing (‘*Limestone, crushed, for mill/CH S*’).

For synthetic salts, potassium nitrate is produced by a reaction of potassium chloride and nitric acid, and this production method is represented in SimaPro. The production of synthetic sodium nitrate was introduced in the Ecoinvent Database in 2016. Due to the absence of data for the manufacture and disposal of $NaNO_3$, $KNO_3$ was considered a valid alternative (Ehtiwesh et al., 2016). Corona et al. (2014) used potassium chloride as an equivalent. For sodium nitrate, there are two potential reactions for its production: via nitric acid and sodium hydroxide and via nitric acid and sodium carbonate. The environmental impacts of the two synthetic reactions are very similar (Burkhardt et al., 2011). Table 6 shows values obtained from SimaPro 9.0.0.35 /Ecoinvent.3.5 for molten salts and some alternatives.

Table 6. Emissions obtained from SimaPro 9.0 /Ecoinvent.3.5 for molten salts.

| | kg $CO_2$-eq per 1 kg<br>Ecoinvent 3.5 / SimaPro 9.0.0.35 |
|---|---|
| Sodium nitrate ($NaNO_3$) | 4.71 |
| Potassium nitrate ($KNO_3$) | 2.28 |
| Salt (60% $NaNO_3$ and 40% $KNO_3$) | 3.738 |
| Potassium chloride as $K_2O$, at regional storehouse/RER/U | 0.334 |
| Potassium chloride, as $K_2O$ (RoW), potassium chloride production APOS/U | 0.506 |

Potassium chloride presents much lower emissions than potassium nitrate. Some authors include the transportation of salts (Burkhardt et al., 2011; Corona et al., 2014), and transoceanic transportation of salt (from Chile) was considered in the case of synthetic salts (Corona et al., 2014).

Table 7 shows the emission values for synthetic salts, according to the different methods employed by the studies (Burkhardt et al., 2011; Klein and Rubin, 2013). Table 7 includes the emissions per MWh produced.

Table 7. Emissions values for synthetic salts.

| Reference | Salt in LCA | kg $CO_{2eq}$ by 1 kg of salt Ecoinvent 3.5 SimaPro 9.0.0.35 | kg $CO_{2eq}$/ MWh (for each author's LCA) |
|---|---|---|---|
| (Viebahn et al., 2008) | Synthetic (60% $NaNO_3$ and 40% $KNO_3$) | 3.738 | 22.65 |
| (Burkhardt et al., 2011) | Mined. Emissions from mined salts from manufacturer | 0.1098* | 0.55 |
| (Kuenlin et al., 2013) | Potassium nitrate, as N, RER<br>Ecoinvent v.2.2 database | 2.28 | -- |
| (Klein and Rubin, 2013) | Mined<br>Sum of data from Vermiculite, at mine/ZA and Limestone, crushed for mill/CH S Ecoinvent | 0.0038* | 0.016302 |
| (Corona et al., 2014) | 60% sodium nitrate<br>40% Potasium chloride, as $K_2O$, at regional storehouse/RER/U | 0.334 | 1.88 |
| (Ehtiwesh et al., 2016) | Potassium nitrate, RER, production, Alloc Def,U<br>Ecoinvent v.3 database | 2.28 | |
| (Mahlangu and Thopil, 2018) | -- | -- | -- |

*(*value according to the author)*

The emissions associated with mined salts are very low in comparison with synthetics salts. Batuecas et al. (2017) calculated the environmental impacts associated with two molten salts, Hitec (2.91 kg $CO_{2eq}$/ kg of salt) and binary molten salt (4.00 kg $CO_{2eq}$/ kg of salt), and with a synthetic oil, Therminol (10.35 kg $CO_{2eq}$/ kg of oil). The results revealed that the impacts associated with Therminol were three times higher.

Burkhardt et al. (2011) provided detailed values for the TES system emissions at each phase, being 5.01 kg $CO_{2eq}$/ MWh for the TES system in wet-cooled configuration, of which 2.7 kg $CO_{2eq}$/ MWh are related to the manufacturing phase.

The thermal capacity of the TES can be employed as the functional unit to report its environmental impact, which is not affected by the plant location. Burkhardt et al. (2011) reported the thermal capacity for both configuration values (wet- and dry- cooled). The obtained impacts are very similar for both configurations, 1,074 and 1,068 kg $CO_{2eq}$/ $MWh_{th}$ TES thermal capacity, respectively.

### 3.6 Comparison of solar fields

The dynamics of meteorological data, such as DNI, are a source of uncertainty and variability regarding the annual electricity production of the plant. The size of the solar field has an essential impact on the environmental assessment of the plant. According to Kuenlin et al. (2013) and Ehtiwesh et al. (2016), the construction of the solar field has the highest contribution to the overall environmental impact.

Table 8 shows the values published by Burkhardt et al. (2011) per $m^2$ of solar field aperture area. The other authors did not disaggregate emissions by subsystem or by phase. Klein and Rubin (2013) reported 9 kg $CO_{2eq}$ /MWh related to the solar field, approximately 5 kg $CO_{2\ eq}$ /$m^2$.

Table 8. GHG emissions per $m^2$ of solar field aperture area.

| (Burkhardt et al., 2011) | wet cooling | dry cooling |
|---|---|---|
| Electricity production (MWh/year) | 426,700 | 438,800 |
| Solar-Field Aperture Area ($m^2$) | 987,500 | 1,063,000 |
| Manufacturing (kg $CO_{2eq}$ /MWh) | 4.6 | 4.8 |
| kg $CO_{2eq}$ /$m^2$ | 1.988 | 1.981 |
| Construction (kg CO2 eq /MWh) | 0.77 | 0.81 |
| kg $CO_{2eq}$ /$m^2$ | 0.333 | 0.334 |
| Operation (kg CO2 eq /MWh) | 2.2 | 2.3 |
| kg $CO_{2eq}$ /$m^2$ | 0.951 | 0.949 |
| Dismantling (kg CO2 eq /MWh) | 0.09 | 0.088 |
| kg $CO_{2eq}$ /$m^2$ | 0.039 | 0.036 |
| Disposal (kg CO2 eq /MWh) | 0.77 | 0.81 |
| kg $CO_{2eq}$ /$m^2$ | 0.333 | 0.334 |
| TOTAL (kg CO2 eq /MWh) | 8.43 | 8.81 |
| kg $CO_{2eq}$ /$m^2$ | **3.643** | **3.636** |

Both plant configurations (wet and dry cooled) present similar environmental impacts regarding the solar field aperture area. This value could be used by researchers at preliminary project stages, focusing on environmental optimization.

The type of parabolic trough collector can affect performance throughout the lifetime of the equipment; moreover, different types of parabolic trough collector require different maintenance/operation activities. Although there is research on the possible improvements in the performance of collectors (Abed and Afgan, 2020), on the different tests for validation of the technology (Sallaberry and Serrats, 2012), and even on the characteristics of life-size test benches for parabolic trough collectors to characterize real prototypes (such as the *Plataforma Solar de Almería*

(León et al., 2014)), however there are no studies that evaluate the deterioration of performance over time. Nor have any studies been found that specifically relate the variation in environmental impact of solar collectors with time. This is an interesting issue, as there are currently numerous CPS that have been operating for many years, and it would be illuminating to develop a study in this direction.

### 3.7 Comparison of the construction and transportation

There are some differences in the LCIs presented concerning the transportation of equipment to the CSP Plant (Table 9). Corona et al. (2014) included transportation of equipment to the plant, disaggregated by subsystem in the manufacturing phase. Burkhardt et al. (2011) also included disaggregation by subsystem; however, the transportation of equipment is included within the construction phase. Other studies included transportation within the construction phase, with no breakdown (Ehtiwesh et al., 2016; Klein and Rubin, 2013; Kuenlin et al., 2013; Mahlangu and Thopil, 2018; Viebahn et al., 2008). These differences affect the results significantly, as some environmental loads shift from the manufacturing phase to the construction phase. Undoubtedly, the transportation included in the inventory data is site-specific and in some cases, ocean freight or rail transportation are also included (Burkhardt et al., 2011; Corona et al., 2014; Ehtiwesh et al., 2016; Kuenlin et al., 2013).

Building and plant facilities, such as administration offices, storage, and parking lots, are included in some LCIs, such as in Burkhardt et al. (2011), where detailed information on plant facilities is included in the construction phase. However, Corona et al. (2014) included building and facilities in the manufacturing phase as additional equipment of the CSP Plant. The remaining authors do not mention any data concerning this part of the plant. The machinery employed is detailed explicitly by (Corona et al., 2014) only.

### 3.8. Comparison of operation and maintenance activities

Some authors include replacement components in the operation and maintenance phases (Burkhardt et al., 2011; Corona et al., 2014; Viebahn et al., 2008). Klein and Rubin (2013) only included the replacement of HTF as a consumable, while others do not include any consumables or spare parts in maintenance activities (Ehtiwesh et al., 2016; Kuenlin et al., 2013; Mahlangu and Thopil, 2018).

The water required for the operation of a CSP plant is mainly used to cool the power block and clean the mirrors. The range of water consumption for operation activities is 2.10 - 3.8 L/kWh for wet-cooled systems and 0.175 - 0.300 L/kWh for dry-cooled systems (Fthenakis and Kim, 2010). Water was not included in the LCI of (Burkhardt et al., 2011; Ehtiwesh et al., 2016; Mahlangu and Thopil, 2018). Corona et al. (2014) assumed a linear relationship between water consumption and CSP Plant power generation.

There are also significant differences regarding transportation requirements during the O&M phase. Some studies included operational auxiliary energy requirements such as electricity and natural gas. Mahlangu and Thopil (2018) included electricity values taken from Burkhardt (+3% of capacity).

Table 9 shows the assumption made for the seven authors.

### 3.9. Comparison of dismantling and disposal

Burkhardt et al. (2011) included the rates of recycling, incineration, and landfilling in the disposal phase. Klein and Rubin (2013) presented the same values as Burkhardt et al. (2011). Mahlangu and Thopil (2018) considered an end-of-life scenario where material was landfilled and disposed as municipal waste. Salts and HTF were sent back to the manufacturer. Transportation was also included. Corona et al. (2014) presented a detailed disposal scenario, where the separated waste is 40% recycled. Ehtiwesh et al. al (2016) contemplated 100% recycling glass, molten salts, and HTF.

The authors who included the diesel burned during dismantling (Burkhardt et al., 2011; Corona et al., 2014; Mahlangu and Thopil, 2018) assumed an amount of fuel proportional to the land area of the CSP plant, based on Viebahn et al. (2008). The diesel consumed to build Andasol I in Spain was estimated as 8800 GJ for 2 km$^2$. Ehtiwesh et al. (2016) considered a meager amount of fuel, ten times lower than what was reported by other authors.

Table 9. Emissions values for construction, transport, O&M and D&D phases

| | CSP Plant | ANDASOL I | Ciudad Real (Spain) | WPG | WPG | ANDASOL | KaXu | --- | ANDASOL |
|---|---|---|---|---|---|---|---|---|---|
| | Net nominal Power (MW) | 46 | 50 | 103 | 103 | 50 | 100 | 11 | 50 |
| | Location | Granada (Spain) | Ciudad Real (Spain) | Daggett (USA) | Daggett (USA) | Sevilla (Spain) | Northern cape (South Africa) | Daggett (USA) | Libya |
| | Reference | (Viebahn et al., 2008) | (Corona et al., 2014) | (Burkhardt et al., 2011) | (Burkhardt et al., 2011) | (Kuenlin et al., 2013) | (Mahlangu and Thopil, 2018) | (Klein and Rubin, 2013) | (Ehtiwesh et al., 2016) |
| Construction Phase | Ground transportation of equipment to the plant (tkm) | IC (2.61E+05) | IMD (2.1E+07)<br>IC (5.06E+07) | ICD (9.59E+07) | ICD (1.04E+08) | IC (7.09E+06) | IC (NA) | NI | IC (1.07E+05) |
| | Ocean freight transportation of equipment to the plant (tkm) | NI | IMD (3.69E+08) | ICD (6.74E+08) | ICD (7.25E+08) | IC (6.03E+07) | IC (NA) | NI | IC (3.13E+08) |
| | Rail transportation of equipment to the plant (tkm) | NI | NI | NI | NI | IC (2.66E+07) | NI | NI | NI |
| | Building and facilities (roads, parking…) | IM | IM | IC | IC | NI | NI | NI | NI |
| | Fuel combusted in building machines during construction phase (GJ) | 19,993 | 8,800 | 40,900 | 41,400 | NI | NA* | NI | 19,990 |
| | Excavation (hydraulic digger) for plant construction ($m^3$) | NI | 61,767 | NI | NI | 1,460 | NI | NI | NA |
| | Construction activities and machinery (crane, concrete mixer…) | NI | Yes | NI | NI | NI | NI | NI | NI |
| | Gravel (kg) | NI | 1.06E+07 | NI | NI | NI | NI | NI | NI |
| O&M Phase | Replacement components used during O&M phase | Yes (0.2% of total embodied mass) | Yes | Yes (5% of total embodied mass) | Yes (5% of total embodied mass) | NI | NI | Only HTF | NI |
| | Ground transportation requirements during O&M phase (tkm) | NI | 4.07E+04 | D (1.02E+07) | D (1.25E+07) | 2.87E+07 | NI | NI | NI |
| | Ocean freight transportation requirements during O&M phase (tkm) | NI | NI | D (1.85E+07) | D (2.00E+07) | NI | NI | NI | NI |
| | Operational electricity from the grid (MWh/y) | NI | 550 | 3,700 | 3,986 | NI | 3,811** | NA | NI |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Operational natural gas requirement (GJ/y) | NI | 6,240 | 9,389 | 16,584 | NI | NI | NA | NI |
| | Fuel combusted during O&M phase (GJ) | NI | NI | NI | NI | NI | NI | Diesel (NA) | NI |
| | Water deionised for maintenance (kg/y) | 3.33E+06 | 1.56E+07 | NI | NI | 3.19E+08 | NI | Water (NA) | NI |
| | Water decarbonised for maintenance (kg/y) | 1.12E+07 | NI | NI | NI | 1.90E+10 | NI | NI | NI |
| | Water for maintenance (kg/y) | 5.45E+08 | 8.28E+08 | NI | NI | NI | NI | NI | NI |
| D&D Phase | Fuel burned in building machines during dismantling (GJ) | 8,800 | 8,800 | 18,000 | 18,200 | NI | NA* | NI | 880 |
| | Ground transportation during dismantling (tkm) | NI | 5.09E+07 | NI | NI | NI | NI | NI | NI |

IC: Included in the construction phase
D: Disaggregated by system
IM: Included in the manufacturing components
NI: not included in the LCI
NA: not available
IE: Included electricity
ING: Included natural gas
* Proportional to land area (Viebahn)
**+3% of difference vs. Burkhardt

### 3.10. Final comments

A detailed, exhaustive analysis has been carried out on the energy systems and different life cycle phases of a parabolic trough CSP plant. The study highlighted the need of developing more specific standards to enable extrapolations and also facilitate comparisons amongst technologies.

Given the broad diversity of environmental indicators developed in recent years, our recommendation is towards the standardization of instruments and indicators. It has been highlighted herein that general parameters, such as lifetime and functional unit, are extraordinarily relevant and must also be uniform and comparable. More specific parameters, appropriate to each technology, must also be standardized (due to its impact, quantity, or even specificity), as has been carried out herein for the HTF and TES (molten salts).

To be able to advance in the same direction, international standards must evolve rapidly, ensuring that the efforts of researchers regarding the sustainability assessment of different technologies, systems, and real applications are comparable. This requirement is fundamental to assure progress towards a world that is much more respectful to the environment.

Solar plants, and especially CSP plants, are demonstrated, advanced, and mature technologies and can undoubtedly benefit from global standardization - this is a great challenge.

## 4. Conclusions

The large amount of data published regarding the environmental aspects of Parabolic Trough Concentrating Solar Power Plants hinders the identification of clear directions and drawing of conclusions to be used during the optimization process of the plant design.

An extensive literature search was carried out to identify LCAs of parabolic trough CSP plants that contained detailed LCI inventories. At the end, only seven studies fulfilled the inclusion criteria and listed detailed LCI. GHG emissions ($CO_{2eq}$) were the most employed indicator in the LCA studies for CSP plants.

The lifetime of the CSP plants and associated systems varied significantly across the studies (from 20 to 60 years), which strongly affected the resulting GHG emissions. Although CPS plants have been oprtaional for a while, the lifetimes is still under validation. Conventional fossil power plants present usual lifetimes of 40 years.

The functional unit employed in the selected studies was the delivery of 1 MWh of electricity by the CSP plant. Environmental results are site-specific as the production depends on the DNI and consequently not comparable with values obtained elsewhere. Therefore, environmental emissions should be normalized for comparison purposes.

Recommendations for reporting the environmental values in future LCA studies for CSP plants include:

- Environmental impact results should be disaggregated by LCA phase and subsystem.
- GHG emissions should be normalized by a parameter of the CSP Plant, such as:
    - For the HTF system, the amounts reported should consider any additional HTF required during O&M phases. The manufacturing processes of the HTF fluid should be described. The total amount of HTF per $MW_e$ reported in literature is approximately 40 $t/MW_e$.

- For TES and molten salts, it is essential to specify whether it is synthetic or mined. The recommended functional unit to report the environmental impact of the complete TES system is its thermal capacity, where the value reported in scientific literature is approximately 1070 kg $CO_{2eq}$/ $MWh_{th}$.
- Regarding the solar field, emissions should be reported per $m^2$ of solar aperture area to avoid dependence on location.
- Equipment transportation (dependent on location) should be disaggregated by phase to facilitate comparison and not overburden specific phases. Sometimes equipment transportation is included within the manufacturing phase or the construction phase, depending on the authors. As these differences affect the result significantly, it is recommended to include transportation impacts in the construction phase and disaggregate by subsystem.
- For the end-of-life scenario, the diesel burned during dismantling must be accounted for, and can be considered proportional to the land area of the CSP Plant (Viebahn et al., 2008).

**Acknowledgments**

The authors thank the Spanish Ministry of Economy and Competitiveness for the funding of this work within the framework of project ENE2017- 87711-R, with the additional support of the Government of Aragon (Spain) (Reference Group T55_17R) and the European Union (FEDER Program 2014-2020: "Building Europe from Aragon”). Thanks are extended to CNPq (Brazilian National Council for Scientific and Technological Development), research productivity grant, nº 307394/2018-2.

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